

THE HISTORY OF GAS IN SPIRAL GALAXIES

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The general association of luminous young stars with spiral arms in galaxies has led to widespread acceptance of the idea that the formation of massive stars, at least, is somehow triggered by the interaction of interstellar gas clouds with a spiral density wave. The observed increase in C/H and N/H with decreasing galactic radius receives a natural explanation in this scenario, as gas closer to the galactic nucleus has more encounters with the spiral density wave. This picture may only be applicable to grand design spirals, since non-grand design spiral galaxies may not have long-lived density waves (Kormendy and Norman 1979).

Consider a very simple model for the gas in such a spiral galaxy, with a specified initial surface density $\sigma(r)$ and angular velocity $\Omega(r)$. A spiral density wave (pattern speed Ω_p) is present. In each encounter with the density wave some fraction f of the gas is permanently lost in the form of low mass stars and stellar remnants. The actual nature of the density-wave trigger is unimportant (e.g., whether the density wave causes HI clouds to coalesce into molecular clouds which then form stars, or causes star formation in pre-existing molecular clouds). The fraction of gas remaining after n encounters with the density wave is just $(1-f)^n$, where f has been assumed constant with time. An assumed initial gas distribution can be evolved back to T years before the present or followed forward in time. If the conversion factors used to infer H_2 column densities from CO $J=1-0$ emission are correct, then H_2 dominates the mass of the ISM for radii less than ≈ 10 Kpc, and the present-day radial gas distributions in spirals are roughly exponential.

Typical results from this simple model, with parameters appropriate to NGC 6946, are shown in Figures 1a and b. The H_2 distribution is from Young and Scoville (1982); Ω_p is from Roberts, Roberts and Shu (1975). Gas profiles have been calculated only for the region of nearly solid-body rotation. Figure 1a shows an initial exponential distribution that has been evolved for 10^{10} years; Figure 1b gives the initial ($T=0$) distribution implied by a present-day exponential distribution. It is evident that a gas distribution that was exponential 10^{10} years ago would now be very flat. A general result is that the gas distributions inferred from CO observations require too much gas in the past, exceeding the dynamical mass derived from the rotation curve.

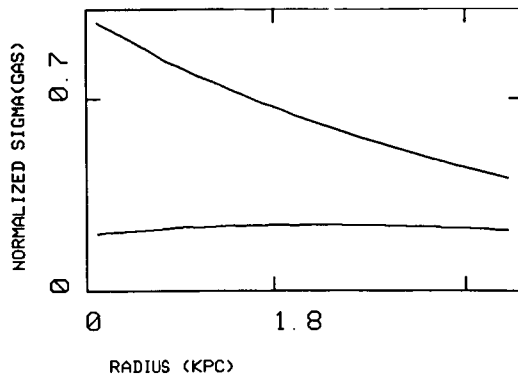


Figure 1a. Upper curve is initial exponential gas distribution; lower curve is gas profile after 10^{10} years. Gas density is normalized to initial $R=0$ density.

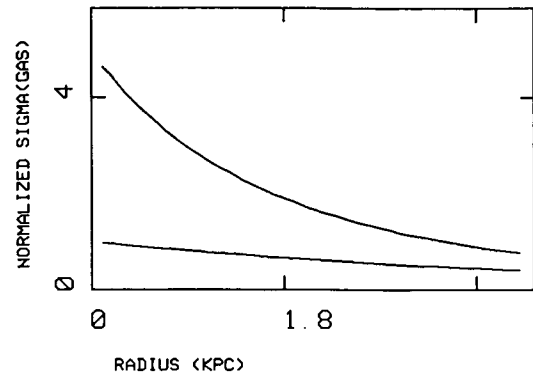


Figure 1b. Upper curve is initial distribution 10^{10} years ago implied by present-day exponential distribution. Normalization as in 1a.

The idea that encounters between spiral density waves and interstellar clouds would lead to depletion of gas at small radii was first suggested by Oort (1974) to explain the distribution of HI in spirals. Possible explanations for this discrepancy are:

- 1) The conversion from integrated CO intensity (I_{CO}) to H_2 column density ($N(H_2)$) is in error. Since linear conversions of this form implicitly assume that all clouds are identical, they almost certainly overestimate the amount of H_2 in the inner region of the galaxy relative to the disk, regardless of the absolute error.
- 2) The star-forming efficiency f is much less than 1%. Note that f as defined above is the amount of gas that is permanently locked up in stars and stellar remnants. This fraction is related to the amount of gas that is turned into stars as a result of the density wave, F , by a factor that depends on the amount of mass returned to the ISM by evolved stars. If only high-mass stars are formed as a result of the density wave (e.g., the lower mass cut-off is $\geq 3 M_{\odot}$) then f would be expected to be $\approx 0.1F$, unless remnants with very large masses are formed. The idea that the initial mass function may be bimodal has been extensively discussed by Larson (1986).
- 3) Grand design spiral structure doesn't persist over galactic lifetimes.
- 4) Our understanding of the effects of density waves on the ISM is very inadequate.
- 5) Infall of gas into the inner disk is extremely important in the evolution of spiral galaxies.

Unfortunately, it is very difficult to make any quantitative statements regarding 2) - 5). Therefore, for the rest of this paper I shall discuss the issue raised by 1), namely: how accurately can we really presume to know the molecular gas distributions in galaxies, based upon observations of CO $J=1-0$ emission?

It has been suggested that there should be a linear conversion between I_{CO} and $N(\text{H}_2)$ if the antenna temperature T_{R}^* effectively measures the fraction of the beam that is filled with clouds. Then, if all the clouds have the same excitation temperature, and are virialized so that the linewidth of each cloud depends on its mass and thus column density, it is claimed that there will be a constant conversion factor between I_{CO} and $N(\text{H}_2)$ (Young and Scoville 1982). Dickman, Snell and Schloerb (1986) (DSS) have made a study of this relation, using a number of simplifying assumptions. However, no rigorous analysis of this suggestion has yet been made, and no study has been made of the errors in H_2 column densities which might result if the assumptions involved are violated.

In order to perform this analysis, a model has been constructed which simulates the observation of molecular clouds in galaxies in a completely general way. A model galaxy is assigned a rotation curve, z-velocity dispersion and inclination. The overall parameters of the cloud distribution (total number, form of radial distribution, etc.) are specified, and a random number algorithm assigns coordinates and z-velocities to the clouds. Cloud velocity dispersions, excitation temperatures, and radii are all assigned individually and may be arbitrarily complicated functions of position. The positions and velocities of all the clouds are projected onto the plane of the sky. Convolution of the cloud brightness distribution with a gaussian antenna (with FWHM $\theta_{1/2}$) is performed numerically, without any simplifying assumptions. Cloud-cloud shielding is explicitly taken into account.

Under what conditions is I_{CO} proportional to $N(\text{H}_2)$? For simplicity, let us consider a face-on galaxy and assign all clouds the same radius and velocity dispersion, σ_c . The surface density of molecular clouds falls off exponentially with radius, in accordance with the distributions inferred using a constant conversion factor. If the clouds all have $T_{\text{EX}} = 10$ K and virialized linewidths, then I_{CO}/H_2 is a constant. However, since $I_{\text{CO}} \propto \sigma_c$ and $\langle N(\text{H}_2) \rangle$, the cloud-averaged column density, is $\propto \sigma_c^2$, the value of the constant depends on σ_c and hence on the mean density. For $\langle n \rangle = 200 \text{ cm}^{-3}$, the value used by DSS, the conversion factor is $N(\text{H}_2) = 2 \times 10^{20} I_{\text{CO}}$. Here $N(\text{H}_2)$ is the column density of H_2 averaged over the beam FWHM. This is 2X smaller than the value advocated by Young and Scoville (1982). It is also smaller than the value of DSS for the same $\langle n \rangle$. This is a result of their neglect of contribution to I_{CO} from clouds outside the FWHM.

Under restricted conditions, then, $I_{\text{CO}}/N_{\text{H}_2}$ is constant, with a value within a factor of two of that suggested for it. The key question then becomes how strongly this ratio is affected by deviations from these restrictive conditions. As mentioned above, clouds must not only be in virial equilibrium, but have the same mean density for $I_{\text{CO}}/N_{\text{H}_2}$ to be strictly constant. This last

condition is very unrealistic. It is not even clear that clouds are in virial equilibrium. In studies of dark clouds, Leung, Kutner and Mead (1982) and Myers (1983) have suggested that these objects are in virial equilibrium, but there is reason to suspect that this is not true (Maloney 1986). If clouds have linewidths that do not reflect their masses, the correlation between CO emission and H_2 column density will cease to be linear.

Of perhaps more importance is the effect of variations in the excitation temperature of the CO J=1-0 line. The models show that, as expected, I_{CO} depends linearly on T_{EX} . Figure 2 shows I_{CO} versus radius for two model galaxies which are identical except that one has $T_{EX} = 10$ K everywhere, while the other has an exponential $T_{EX}(r)$, with $T_{EX}(0) = 40$ K and $T_{EX}(15 \text{ Kpc}) = 5$ K. Figure 3 shows $N(H_2)$ versus R obtained using a constant conversion factor, as well as the actual $N(H_2)$ distribution. A T_{EX} gradient of this size will lead to an error of an order of magnitude in the inferred H_2 mass between the center and edge of the disk.

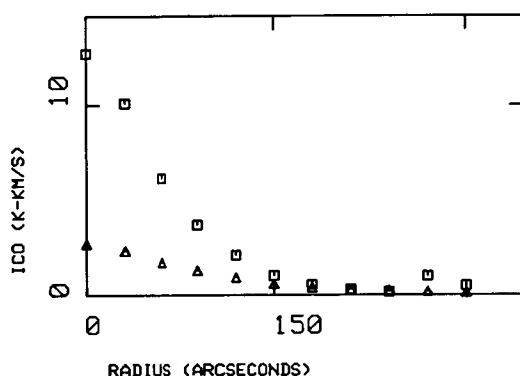


Figure 2. Integrated CO intensity vs. R ($20''=1 \text{ kpc}$) for model with exponential T_{EX} (boxes) and constant T_{EX} (triangles).

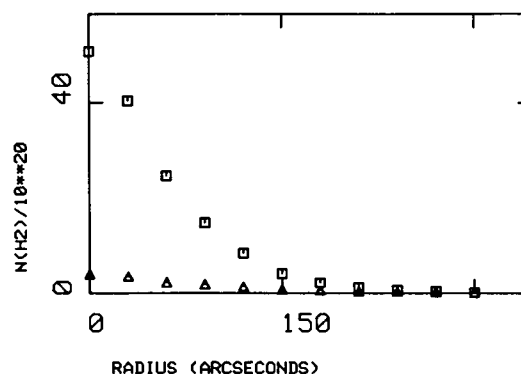


Figure 3. Actual $N(H_2)$ distribution (triangles) and distribution inferred from $I_{CO}/N(H_2) = 4 \times 10^{20}$. $N(H_2)$ in units of 10^{20} cm^{-2} .

It is apparent that large errors in H_2 mass within a galaxy are possible when using a constant $I_{CO}/N(H_2)$ conversion, with the result that the actual gas distribution may be considerably different from what is inferred from CO observations. In the absence of information on the actual variation of excitation temperature across a galaxy, caution must be exercised in the use of such conversions.

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